POWER AND PROPULSION FOR THE EXPLORATION OF SPACE

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FOREWORD:

Before proceeding with my lecture, I would like to express my appreciation to Prof. Ing. Tabanera, chairman of the symposium committee, for inviting me to take part in this historic meeting in Argentina. Through the vision of Prof. Tabanera and of other scientists and engineers, Argentina early gained a world-wide reputation for interest in space research and technology and in the exploration of interplanetary space. I first met Prof. Tabanera at the Fifth International Astronautical Congress held in Innsbruck, Austria, August 2, 1954. He was at that time the second vice-president of the International Astronautical Federation, and I was a visitor from the aeronautical sciences. Later, we worked together on the Technical Committee of the United Nations Ad Hoc Committee on the Peaceful Uses of Outer Space, hoping to achieve a basis for widespread international cooperation in space research. I believe most sincerely that advances in the understanding of our universe are not the prerogative of a single nation or group but come from every quarter of the world in which scientists are active. I am sure that Argentina will make increasing scientific contributions to the exploration of space under the leadership of the Commission for Space Research.

INTRODUCTION:

For many centuries astronomers have been studying the celestial bodies and interplanetary and intergalactic space by indirect methods. The information obtainable was that borne by the light waves, and, in recent times, radio waves reaching observing instruments on the surface of the earth. The earth's atmosphere is opaque to certain regions of the electro-magnetic spectrum and the variable properties and motions of the atmosphere introduce perturbations which interfere with precise observations. Nevertheless, a tremendous amount of knowledge has been gained about the dimensions, chemical composition, physical state, relative positions and motions of the celestial bodies and about the extremely small amounts of matter and the radiation in interplanetary space.

The development of rockets for military purposes during and after World War II brought into existence the means of exploring the high atmosphere and nearby space by direct methods. Scientific measurements can now be made by transporting apparatus to great distances above the surface of the earth. Here we may study directly at the scene the phenomena to be investigated and we can make indirect measurements of celestial objects in the same manner as at the earth's surface but free from the absorption and perturbation of the atmosphere. The spacecraft available include sounding rockets, earth satellites, and man-made planets travelling around the sun.

Much progress has been made already but we look forward confidently to greater accomplishments, to the sending of instruments to the moon, Mars, and Venus, to man's first venture into space, first in a ballistic flight to high altitude, then in orbital flight, to manned landing on the moon and return, and so on into the distant future.

In all of this activity involving the transport of instruments and men for the exploration of space, the possible accomplishments are directly dependent on the power and propulsion available at the time. The propulsion system was and is the key to exploration in space as it has been for exploration on the sea, on land, whether in the desert, polar regions, or mountain trails, and in the atmosphere.

The present paper gives a broad review of the space power and propulsion picture as it now stands and as it seems to be developing. The essential elements to be discussed are the source of energy, either for propulsion or for operating the on-board equipment; the propulsive or thrust-producing element, including the working fluid; and energy conversion methods.

An account will be given of the propulsion and power systems in use and under development by the National Aeronautics and Space Administration. Sounding rockets will be omitted, since they are described by Dr. Newell in a later paper at this symposium. In other words, this paper treats the propulsion systems for satellites, deep space probes, and man-made planets. A primary objective is to give an overall framework for the more specialized technical papers on propulsion which are to follow during the course of the symposium.

ENERGY SOURCES:

Every space vehicle must have access to a supply of energy for propulsion and for operation any on-board equipment such as scientific instruments, communication equipment, attitude control, life-support equipment, et cetera. The only known sources of energy are those which release energy by chemical reactions or nuclear reactions. In more specific terms the common chemical sources are the fuel and oxidant supply in the tanks of a chemical rocket, electric batteries which contain a supply of energy in chemical form, and the food supply for human occupants which may be converted into muscular energy useful for some purposes. The common nuclear sources are radio-isotopes, nuclear reactors, and the sun whose energy results from nuclear reactions. Small amounts of energy for special purposes may be stored in compressed gas bottles and compressed mechanical springs.

With the exception of the sun, the other energy sources, i.e. chemical fuel, nuclear fuel, food, must be carried on-board the vehicle from the earth or provided by another vehicle sent from the earth for resupply. Any given supply provides a limited amount of energy and thus provides for a definite life-time at the nominal rate of use. Chemical batteries and food are exhausted relatively soon; nuclear fuel contains much more energy per unit mass and thus nuclear devices provide a much longer life. In the distant future, it may be possible to greatly extend flight duration by the development of breeder reactors which produce additional nuclear fuel within the reactor and by developing carbon, oxygen, water, and other chemical cycles in a closed ecological system for man himself using solar energy.

Solar energy is the only source which is virtually inexhaustible and requires no continual consumption of on-board supplies, but is available only when the spacecraft is in sunlight. There have been proposals to supply energy to a spacecraft by electromagnetic radiation from the ground rather than by physical refueling but this method does not appear practical at the moment.

The available chemical sources of energy include a wide variety of substances. Energy is released generally by the reaction of a "fuel" with oxygen, although some substances are used to release energy by decomposing into simpler compounds. The fuel is usually a compound containing one or more of the lighter elements in the first four groups of the periodic table, i.e., hydrogen, lithium, beryllium, boron, carbon, magnesium, aluminium. The "oxidizers" contain oxygen or fluorine, usually bound to other elements such as nitrogen or chlorine. The substances of interest are those containing elements of low molecular weight, partly because of their generally higher energy release per unit mass on oxidation and partly because these elements are more effective in producing thrust as used in rockets.

The "Rocket Propellant Handbook" of Boris Kit and Douglas S. Evered (MacMillan Company, New York, 1960) lists 90 or more substances used as rocket propellants, all of which are composed of the elements previously named and in a few cases also sildcon, sulphur, and potassium as combining elements. The number of possible chemical energy sources is of course much greater than the 90 named.

In the case of certain simple substances such as hydrogen, the release of energy requires the chemical reaction of two substances, one containing the fuel element, the other the oxidizer, stored separately. In other substances such as nitromethane, CH_2NO_2, the elements carbon and hydrogen and oxygen are contained in the molecules of a single substance which may be decomposed to form hydrogen, nitrogen, water, carbon monoxide, and carbon dioxide with release of energy. Much more complex substances are used as solid propellants. Modern solid propellants consist of mixtures of many substances, usually two principal ones with many others in small amounts to serve as stabilizers, vulcanizing agents, burning rate accelerators, etc. Detailed knowledge of the proportions and processes used are often proprietary secrets of the manufacturer.

S.H. Dole and M.A. Margolis of the Rand Corporation (in a paper presented before a recent meeting whose proceedings have been published under the title, "The Chemistry of Propellants" by Pergamon Press, New York, 1960) list the following "menu" of presently available and prospective rocket propellants:

	PRESENT	POST 1961
Liquids		
Cryogenic	Liquid oxygen Hydrocarbon Fuel R.P.	Liquid fluorine Hydrazine or Liquid hydrogen Liquid oxygen
Storable	Nitrogen tetroxide Unsymmetrical dimethyl hydrazine	Chlorine trifluoride Hydrazine
Solid	Ammonium perchlorate and polyurethane	Ammonium perchlorate Organo-Boron

PRODUCTION OF THRUST:

Propulsion is space can be accomplished only by applying the available energy to the production of a force acting on the spacecraft, commonly called the thrust. The only known method of producing a force on an isolated system in space is to apply energy to continuously change the momentum of some substance used as a working fluid. The thrust developed is equel to the time rate of change of the momentum of the working fluid. For the present and for some time in the future the working fluid must be carried along from the ground. The rate of consumption and available supply of the working fluid determine the total time during which thrust can be developed.

In the chemical rocket the working fluid consists of the products of combustion of the energy scource. The chemical energy is converted to the internal energy of hot, high-pressure gases which are expanded through a nozzle to form the propulsive jet. It is desired to obtain the highest possible thrust for a given rate of consumption of working fluid. The ratio of the thrust produced to the mass rate of flow of working fluid is known as the specific impulse and is a useful measure of the effectiveness of the propulsion system. It is a function of the chemicals uased and of the expansion ratio of the rocket nozzle. For a given expansion ratio the specific impulse is proportional to the square root of the ratio of the absolute temperature of the gas in the combustion chamber to the mean molecular weight of the working fluid. The permissible temperature is limited by the properties of the materials used and the effectiveness of cooling in reducing the temperature of the wall of the combustion chamber below the gas temperature. The molecular weight should be as small as possible to produce the highest specific impulse; hence the chemicals used should be composed of the lighter elements near the beginning of the periodic table.

If a nuclear energy source us used, the nuclear fuel does not furnish working fluid to produce thrust. Hence a separate supply must be used. Since hydrogen is the substance of lowest molecular weight, it is preferred. In the nuclear thermal rocket, the nuclear energy is used to raise the temperature of the working fluid which then expands through a nozzle as do the combustion products in the chemical rocket.

If energy is stored in compressed gas in a tank, this gas may be used also as working fluid to furnish forces for attitude control, spinning or despinning, vernier corrections to the trajectory, et cetera.

It is possible to use charged particles, specifically positive ions, as a working substance. Acceleration of charged particles could be accomplished by a suitable electric field. In this case it is found that the specific impulse is proportional to the square root of the ratio of the product of electrical charge times electric field strength to the molecular weight. Such a device is not temperature-limited. However, the energy required to ionize the working fluid represents a loss. The ionization energy is high for elements near the beginning of the periodic table and hence it proves desirable to go to working fluids of small ionization energy such as cesium. Nevertheless because the voltage is not limited, it appears feasible to obtain much higher specific impulses than for chemical or nuclear rockets.

With ions as working fluid it is necessary to accelerate the electrons removed in the ionization process and feed them back into the ion jet to avoid adverse decelerating electric fields at the discharge. At sufficiently high temperatures the ions and electrons can remain near each other without recombining and by accelerated by a suitable combination of electric and magnetic fields. Instead of ions, charged colloidal solid particles may be used as a working fluid to be accelerated by electrical means.

Although the specific impulse of ion and plasma jets is very high, the thrust to weight ratio of complete systems is very low, because of the great weight of the electrical generating equipment. The thrust obtainable is very low, usually less than a kilogram from a propulsion system weighing thousands of kilograms. Hence such working fluids are useful only where the component of the gravitational force in the thrust direction is small, i.e., at great distances from the earth and other celestial bodies where the gravitational force is negligible or for slow changes in trajectories where gravity is balanced by centrifugal forces as in an orbiting satellite.

Conceptually the charged particles existing in space might be used as a working fluid. Likewise, since radiation has an equivalent mass, it too might conceptually be used as in the proposed photon rocket. But such uses seem far away.

There have been proposals to use the pressure of radiation to produce a force, for example, by reflection of solar sail. The force can be calculated and it may be of interest to you to learn that solar radiation pressure does modify the orbit of the Echo satellite, a lightweight balloon 30 meters in diameter. The observed effect corresponds to that predicted and produces a considerable reduction in the estimated lifetime of the satellite, reducing if from about three years to about one year.

ENERGY CONVERSION:

The basic chemical, nuclear, and solar energy sources provide energy initially in the form of heat or electrical energy. For propulsion and attitude control the energy must be converted to kinetic energy of the working fluid. For on-board power to operate equipment, energy is required usually in the form of electric power of the appropriate voltage, current, and frequency. In most spacecraft to date, one energy source, a chemical one, has been used for propulsion and another, chemical batteries or solar, for supplying the internal power. Ultimately, when electrical propulsion is employed, a single system may be used, at least in the spacecraft itself.

As already mentioned, the conversion from the heat energy supplied by chemical or nuclear reaction is first converted to the internal energy of the hot working fluid, and as much as possible of this internal energy is converted to mechanical energy of the jet by expansion through a rocket nozzle. If the working fluid is a plasma or ions, the energy released in the form of heat must first be converted to electrical energy and then to the kinetic energy of the jet by a suitable electrical accelerator. Under this concept, both rocket engines and ion and plasma engines are to be considered energy conversion devices as well as producers of thrust. In an accelerating rocket the total energy released goes partly to the kinetic and potential energy of the rocket and remaining propellants and partly to the kinetic energy of the expelled working fluid.

For on-board spacecraft power the energy must be converted to electrical form. At present chemical and solar energy sources are used, the conversion devices being batteries and photovoltaic solar cells. When solar cells are used, battery capacity is provided to store sufficient energy during the time the spacecraft is in sunlight to operatethe equipment when the spacecraft is in the shadow of the earth. Reasonably good results have been obtained for small amounts of power, although some problems have arisen with respect to deteriorating performance of storage batteries in a vacuum on multiple recycling at high ambient temperatures, and with radiation damage to solar cells from protons and electrons in the Van Allen radiation belts and from solar flares. Solar cells are still very expensive, the cost being of the order of $ 500 per electrical watt.

There ar e three energy conversion systems which may be used with chemical, with nuclear, or with solar energy sources. These are mechanical, thermoelectric, and thermionic systems. In the mechanical systems the heat released from any of the sources is used to heat a working fluid which drives a turbo-electric system. If solar energy is used, energy for the dark operation may be stored either as thermal energy or as electrical energy. Except for the lighter weight and greater refinement of design such systems are generally similar in operation to the familiar electric power generation stations used to supply power to our homes from coal or oil. With chemical energy the heat is generated by a combustion process; with nuclear energy by fission, and an intermediate heat transfer medium may be used to avoid radioactive contamination of the working fluid of the turbine.

The simplest form of thermoelectric converter is a thermocouple made by joining wires of dissimilar material. When heat is applied to one junction, an electric voltage is generated. The Atomic Energy Commission has developed a small unit, SNAP-3, in which the energy source is a radioisotope, and the conversion to electric power is made by thermoelectric units. This unit furnishes about five Watts of electrical power, and is intended as a demonstration unit or prototype.

The thermionic converter is based on the emission of electrons from a hot surface to a nearby cold surface thus obtaining an electric current. These devices are in an early stage of development.

In addition to the three energy conversion systems suitable for use with all of the energy sources, there is a fourth capable of direct conversion from chemical to electrical energy. This is the fuel cell, which consists of a cell filled with an electrolyte in which electrodes are inserted. Instead of passing electric current through the solution to decompose it as in the ordinary electrolytic cell, chemicals are fed into the solution to recombine and generate an electric current. Typical fuels are hydrogen and oxygen.

PRESENT LANCH VEHICLES AND SPACE MISSIONS:

Having reviewed the basic principles and concepts relating to energy sources, production of thrust, and energy conversion let us turn to the program of activities of the National Aeronautics and Space Administration. With the exception of the IGY Vanguard program, all of the NASA space missions so far accomplished have used launch vehicles whose first stages were developed by the Department of Defense for the ballistic missile Program. These first stages are slightly modified Jupiters, Thors, and Atlases. With the addition of the Vanguard second stage and other specially built upper stages and payloads, we have been able to proceed immediately to explore the space environment, without awaiting the development of new launch vehicles specifically for space operations. The missions which can now be undertaken are limited by the capacity of the presently available vehicles and the development of launch vehicles of greater capacity was initiated at the beginning of the space program.

We have been able to accomplish a great deal with the presently available vehicles and you will be hearing about some of the results during the symposium. Let me mention briefly two of our most successful satellites, Tiros I and Echo I.

(please turn over)

Tiros I, the meteorological satellite, made 378 trips around the earth in its first two months, producing more than 20,000 photographs of cloud formations over the earth between latitudes 50 ° N to 50 ° S. Tiros I was launched successfully on April 1, 1960. It is a 270-pound satellite launched into a nearly circular orbit with maximun and minimum altitude of 468 and 435 miles, respectively. The period is 99.15 minutes, It is stabilized by s pinning. Thus manintaining a nearly fixed dire ction in s pace. Pictures are obtained in that part of the orbit where the ca.mers sees the s unlit portion of the earth. The satellite is provided with tape recorders which can record as many as 32 pictures for later transmission when the satellite is within range of one of the two ground stations. Meteorologists tell us that bhe value of these photographs to their work has greatly exceeded their already high expectations. For example, in the southern ocean areas where previously the only observations available were those from less than a dozen ships, Tiros produced pictures which gave an overall view of cloud formations, showing the exact locations of four storm centers. Weather fronts are easily located. Previously unknown spirally banded cloud formations in storms of moderate intensity were seen for the first time extending over thousands of square miles, The Chief of the Wheather Bureau has told us that the meteorological satellite is the most significant development in meteorology in all time of greater importance than the invention of the barometer. Echo I, the passive communications satellite, was launched on August 12, 1960 into a nearly circular orbit at an altitude of about 1000 miles. The satellite is an inflatable sphere 100 feet in diame which constitutes a small "moon" from which radio signals have been reflected to give excellent quallity communication between California and New Jersey. It is made of thin Mylar plastic coated with aluminum and weighs about 132 pounds. These two satellites are first steps in the early application of earth satellites to practical uses for human benefit. Research and development in this area will be continued to provide prototipes for satellites to be used in operational systems for weather observation and forecasting and for long-range radio communication links of great traffic capacity.

LIQUID PROPELLANT LAUNCH VEHICLES

In the early stages of the NASA program many types of launch vehicles have been used. Since, however, reliability increases with the number fired, many of the older vehicles are being phased out to concentrate on a relatively small number of types. The oldest launch vehicle now in use is the Juno II, based on the Jupiter first stage. Three more missions remain, after which use of this vehicle will be discontinued. Juno II is a four-stage vehicle, the second stage consisting of eleven solid propellant rockets (Sergeant Jr.) in a cluster, the third of three similar rockets, and the fourth of one, Its overall weight is 12k,000 pounds and it can place 95 pounds in a 300 nautical mile orbit. The Jupiter first stage utilizes the conventional liquid propellants, liquid oxygen (LOX) and hydrocarbon fuel. The Thor-Able launch vehicle also to be phased out, consisted in its original version of a modified Thor; a second stage which was a modified form of the Vanguard second stage, and a third solid-propellant stage (Altair) also based on an earlier Vanguard design. Its overall weight was about 105,000 pounds and it launched the 142 pound Explorer VI into an elliptical orbit with perigee of 156 and apogee of 26,357 miles. The first stage propellants were liquid oxygen and hydrocarbon fuel; the second white fuming nitric acid and unsymmetrical dimethyl hydrazine. Later versions of Thor-Able used larger fuel tanks in the second stage and provided a restart capability. One such version launched the 270 pound Tiros I into a nearly circular orbit, at about 450 miles.

The Delta vehicle, of which ten remain to be fired, uses essentially the Thor-Able hardware with some reliability and performance improvements and with addition of a highly accurate guidance system adapted from the Titan program. Its launch weight is 112,000 pounds and it has the capability of placing 480 pounds in a 300 mile orbit. Delta launched the 132 pound Echo I sphere, its 30 pounds of inflation powder and 28 pounds of packaging into an approximately 1,000 mile orbit. Delta also will be replaced by Thor-Agena at the end of the present series.

The Thor-Agena B, developed by the Department of Defense for the Discoverer program, consists of a Thor and a second stage which is a modified and enlarged version of the second stage that has been used very successfully in the early Discoverer program. It will replace the Juno II, Thor-Able, and Delta in the future NASA program. The second stage propellants are the same as in Thor-Able and Delta, white fuming nitric acid and unsymmetrical dimethyl hydrazine. The weight of Thor-Agena B is 123,000 pounds and it has the capacity to place 1,600 pounds in a 300 mile orbit.

Modified Atlases and Redstones are being used in the manned satellite program.

The Atlas-Agena B is similar to Thor-Agena B with substitution of Atlas for Thor to gain a greater capability. This vehicle will also be used in Air Force missions, and this common use is expected to realize a high reliability at an early date. Atlas Agena B weighs about 275,000 pounds and will place 5,000 pounds in a 300 nautical mile orbit. It can launch about 750 pounds to escape velocity, and will be used for early lunar exploration as well as for scientific satellites.

The vehicles so far mentioned utilize the relatively low energy chemical propellants, but we are moving in future leanch vehicles to the use of the high energy chemical propellants, liquid hydrogen and liquid oxygen. This combination gives us a specific impulse of something over 400 seconds as compared to something under 300 for the fuels presently in use.

The first use of liquid hydrogen-liquid oxygen will be in the Atlas Centaur, a vehicle consisting of an Atlas with a new second stage using the high-energy propellants. The development of this vehicle is well along and it is hoped to make the first flight about the middle of next year. The present weight estimate is about 290,000 pounds with an estimated capability of 8,500 pounds in a 300 mile orbit, and about 1,500 pounds to the vicinity of Mars or Venus.

The largest space launch vehicle now under development is the Saturn. The Saturn C-1, presently under active development, is a three-stage version giving the earliest availability. It will be followed by a four-stage version Saturn C-2. The first stage, called S-1, of each version utilizes a cluster of eight engines which are uprated versions of the Thor engine to 188,000 pounds thrust. The total thrust will therefore be 1½ million pounds. The second stage of C-1 which will also be the third stage of C-2 is called S-IV. It utilizes four Centaur engines uprated to 17,500 pounds providing a total thrust of 70,000 pounds. This and all upper stages of Saturn will use liquid hydrogen and liquid oxygen.

The third stage of C-1, which will be the fourth stage of C-2, is the Centaur stage slightly modified to use the uprated engines, giving a stage thrust of 35,000 pounds.

The second stage of the propsed Saturn C-2, termed S-II, will be a new development requiring a new hydrogen-oxygen engine of 200,000 pounds thrust. Development of the engine has been initiated. The designation S-III was reserved for the third stage of a possible Saturn C-3 of five stages, but no development of it is presently contemplated.

Flight tests of the S-I stage are scheduled for next year and it is hoped to launch the first complete Saturn C-1 in 1963. The estimated weight is one million pounds. Its total height will be 185 feet and its maximum body diameter 21½ feet. Its estimated capability is 19,000 pounds in a 300 mile orbit and 6,000 pounds to escape. About 1,000 pounds could be sent to a soft landing on the moon.

The Saturn is intended for use in a variety of missions, exploration of the moon and planets with considerable payloads, and extending the manned exploration of space.

In addition to the developments of the Centaur and Saturn launch vehicles, we are developing a large single-chamber chemical rocket of 1½ million pounds thrust, as a unit which would serve as a basis for engine clusters having thrusts of six to twelve million pounds. We are also doing limited research and component work with liquid hydrogen and liquid fluorine, which gives somewhat higher impulse. However, fluorine is extremely toxic and corrosive and presents many operational problems.

SOLID PROPELLANT LAUNCH VEHICLES:

Solid propellant rockets have been used for sounding rockets and upper stages of satellites and space probes as well as for generating small forces for spin and despin, vernier corrections, et cetera. The family of launch vehicles under development includes one using solid propellants throughout. It is the Scout, a 36,000 pound, four-stage vehicle, about 72 feet long capable of orbiting about 150 pounds in a 300 mile orbit. Its development originated in an aerodynamic, structural, and heat transfer program carried out with solid propellant rockets. The technology progressed to multi-stage rockets of larger and larger size. Its component stages are derived by small improvements in rockets developed for other purposes. For example, the fourth stage is the improved Vanguard fourth stage also used in Thor-Able and Delta. This stage, Altair, weighs 520 pounds and has a thrust of 3,100 pounds. The first stage, Algol, weighs 23,600 pounds and has a thrust of 105,000 pounds. The second stage, Castor, weighs 9,300 pounds and has a thrust of 55,000 pounds. The third stage, Antares, weighs 2,600 pounds and has a thrust of 13,600 pounds.

Scout has carried a 120 pound payload to an altitude of 3,500 miles in a ballistic flight to a horizontal range of 5,800 miles. The next flight will be an orbital experiment.

We have carried out studies concerning potential advantages of much larger solid rockets and we are following with great interest research to obtain solid propellants of greater specific impulse, developments to permit assembly of loaded solid propellant rockets from pieces more easily transportable to the launch site, and other developments. The Department of Defense and NASA are supporting work in these areas. In the present state of the art, the higher specific impulse obtainable from liquid propellants is required for many space missions.

NUCLEAR ROCKETS:

Nuclear fission as an energy source for space propulsion promises spectacular gains on difficult missions, whether for sending very large payloads into nearby space or substantial payloads to great distances. There are at least two attractive lines of development; one the use of a conventional working fluid, hydrogen, expanded through a nozzle as in the chemical rocket; the other the conversion of the energy to electrical energy and the use of one of the forms of electrical propulsion. Let us first discuss the nuclear thermal rocket, on which substantial research and development has already been acco mplished.

The nuclear rocket program, Rover, is a joint effort between NASA and the Atomic Energy Commission. The AEC is responsible for developing the nuclear reactors, while NASA is responsible for all non-nuclear components, and for integrating the engine into a flight vehicle. We have recently established a joint office to manage the program.

The first KIWI, or ground test, reactor was successfully tested in the summer of 1959. Since then, there have been two more successful tests this summer, and plans call for a third next year. With each test, the KIWI reactor and its associated plumbing are being modified to more nearly approach a prototype flight-weight engine system. NASA is now evaluating proposals from industry on a preliminary design study of a complete engine. In addition, industrial contractors are engaged in parallel studies of the requirements to be met for flight testing. Also, a competition is under way for preliminary design studies of test facilities which will be required for further ground test of the nuclear engine and the nuclear-powered vehicle.

ELECTRIC PROPULSION:

Our program in the electrical propulsion field is aimed toward the development of engines based on the use of ions and plasma as working fluids with which to achieve the advanced missions of the next decade and beyond. Research is now being supplemented by specific advanced developments of the engines or thrust elements to match electrical power system developments to be described later.

The characteristic features of electrical propulsion systems are the high specific impulse and the low thrust. Specific impulses of 5,000 to 10,000 and thrusts less than one or two pounds are characteristic values under discussion.

The types of thrust generators under consideration are: (1) electrothermal, in which the electrical energy is used to heat a conventional working fluid by means of an arc or a resistance heater; (2) electrostatic, in which ions or colloidal particles constitute the working fluid and are accelerated by an electrostatic field; and (3) electromagnetic, in which a plasma is accelerated by a crossed magnetic and electric field system or by a travelling magnetic wave system.

Three applied research and development projects have been established in the NASA program, two in the first category and one in the second. Feasibility studies of the third category are included.

The first development project is for a one kilowatt arc-jet engine to develop the force required to provide the necessary torque to control the angular orientation of a spacecraft.

The second development is that ot an arc-jet engine to be flight-tested with the SNAP-8 nuclear electrical power supply to be described later. Such a system could be used for transfer from a parking orbit to a 24-hour synchronous orbit with considerable improvement in payload over chemical rocket propulsion.

The third project aims to develop engine and propellant feed system components for a 30-kilowatt cesium ion rocket engine which will generate a thrust of 0.1 pound. Ion engines show great promise for planetary missions.

SPACE POWER GENERATION:

The NASA program for the development of space power generation systems has been planned in the light of the estimated requirements. Nearly all the vehicles scheduled for the next four years require average power levels below 250 watts. Power in these amounts can be readily provided by solar cells in combination with batteries. Beginning in about 1965 the Saturn spacecraft will come into use with requirements for the proposed missions ranging from one to four kilowatts. When electric propulsion becomes available, it is estimated that the requirements will rise to values from 50 to 1,000 kilowatts.

Development has been initiated of a three kilowatt system using solar power, turbo-electric conversion, and thermal energy storage known as Sunflower I. The solar energy is collected by a large parabolic reflector with a boiler at its focus. The turbo-electric system is based on a mercury Rankine cycle, and the energy storage for operation in the earth's shadow uses molten lithium hydride. Specifications require the system to be capable of generating three kilowatts continuously for one year in any earth satellite at an altitude between 300 and 20,000 nautical miles. The target weight is about 700 pounds exclusive of the sun orientation system.

NASA is developing jointly with the Atomic Energy Commission a 30-kilowatt nuclear turbo-electric system known as SNAP-8. This system also uses mercury as the working fluid in the turbine. The estimated weight is about 2,000 pounds. It is hoped to carry this development to the point of one year operating life.

In addition to these specific developments, applied research is being conducted in such areas as the effect of the space environment on materials (emissivity and meteoroid damage), liquid-metal and vaporized-metal technology, and high temperature components of the Rankine cycle system.

NASA plans to support research on cesium vapor thermionic converters for use with solar power and on the feasibility and practicability of fuel cells for space missions.

CONCLUSION:

To summarize, NASA has under development space propulsion and power conversion systems to make possible rapid progress in the exploration and utilization of space. A large first-stage rocket, the Saturn, will provide a take-off thrust of $1\frac{1}{2}$ million pounds using liquid oxygen and hydrocarbon fuel. A new single-chamber rocket engine of $1\frac{1}{2}$ million pounds thrust provides an engine which can be clustered to give still higher thrusts. As rapidly as possible, an upper stage using liquid hydrogen and liquid oxygen will be brought into use to increase payloads on Atlas, and such stages will be used from the beginning with Saturn. A nuclear rocket using hydrogen as the working fluid is in the research and evelopment stage to be used first in an upper stage of Saturn. In the electrical propulsion field, arc jets of one and 30 kilowatts rating and a 30 kilowatt cesium ion rocket are under development.

In the power conversion area, the principal developments in progress are a solar-turbo-electric system of three kilowatts capacity and a 30 kilowatt nuclear-turbo-electric system.

These are the space propulsion and power tools to be used in the NASA program in the next decade. The conduct of this program would be impossible without the support of scientists and engineers in many other countries. I hope that most of you will feel that the program is being carried out for your benefit as well as our own, that it is in a certain sense your program too. I am very pleased to see on the program contributions arising from your own cooperative acti vity with NASA and I wish to take this occasion to express our thanks and appreciation. We are proud to be associated with Ing. R. Monges López, President of the Mexican-U.S. Commission for Space Observations Relative to the Mercury Project, who has added his efforts to ours in the best traditions of international science. Our many colleagues on this continent who have joined in the work of tracking and telemetry at the several optical and Minitrack stations are represented on the program by Ing. R.F. Woodman of the Geophysical Institute of Huancayo, Peru. Finally, there are many of you engaged in scientific research in astronomy and geophysics in ground facilities whose observations joined with those obtained from satellites and space probes produces a greater harvest of new information than either program alone. It is to you, my colleagues, that I have made this report of the tools that will support our joint efforts in the near future.

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